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Diagnosis of In Situ Air Sparging Performance Using Groundwater Pressure Changes During Startup and Shutdown

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In the past few years it has become increasingly common to use pressure transducers (rather than water level tapes) to measure groundwater pressure changes during In Situ Air Sparging (IAS). Pressure measurements allow nearly continuous data collection and, when used in conjunction with piezometers with short screens provide data with increased freedom from artifacts.

Groundwater pressure measurements provide a number of insights into IAS operation. For example, the time required for pressure to return to pre-sparge levels (within a few cm of water) is a good estimate of the time required for sparging air flow to reach steady state. This measured time then can be used to determine frequency of pulsing cycles for air injection during IAS as recommended in Johnson et al. (2000). Pressure measurements can also be used to identify sites at which significant volumes of air are becoming trapped below the water table. In that context, the data can be used as a red flag during pilot tests to indicate whether IAS may be infeasible at a site.

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Diagnosis of In Situ Air Sparging Performance Using Groundwater Pressure Changes During Startup and Shutdown

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1.0 BACKGROUND

Air behavior during in situ air sparging (IAS) is a complicated multi-phase flow problem that is very difficult to predict in advance, even with extensive site characterization. As a consequence, a number of approaches for measuring air distribution during initial system operation have been proposed. Historically, one of the first-used approaches was to monitor water level changes during IAS startup. Frequently, the lateral extent to which changes in water levels in wells were observed was interpreted as a measure of the radius of influence of a sparging system. This has led to a general overestimation of the zone (radius) of influence because water pressure changes propagate farther than the air actually does. Pressure also propagates in a much more symmetrical manner radially than air actually does, and this has often led to the erroneous conclusion that sparging was occurring uniformly around IAS wells.

Early practitioners of sparging also sometimes reported sustained changes in water level during IAS. Some of these reports may have been due to measurement errors (e.g., the use of water level tapes combined with IAS air entrained in the water in the well bore would indicate higher than actual water levels). This led to concern about enhanced migration of contaminants away from the sparge well. Although there may be isolated sites where this is a problem, the authors are not aware of a documented case where this has actually occurred, and therefore it is generally thought not to be an important issue.

In the last few years it has become increasingly common to use pressure transducers (rather than water level tapes) to measure groundwater pressure changes during IAS operation. Pressure transducers allow nearly continuous data collection and, when used in conjunction with piezometers

with short screens, increased freedom from artifacts. As a result, pressure data are more frequently being used as a reliable diagnostic tool for IAS (Johnson et al, 2000a ; Lundegard and Labrecque, 1997). Figure 1 illustrates the use of pressure transducers to measure water pressure during IAS startup.

Groundwater pressure measurements provide a number of insights into IAS operation. For example, the time required for pressure to return to near pre-sparge levels (within a few cm of water) is a good estimate of the time required for air flow to reach steady state. This time can then be used to determine frequency of pulsing cycles for air injection during IAS as recommended in Johnson et al. (2000). Pressure measurements can also be used to identify sites at which significant volumes of air are becoming trapped below the water table. In that context, the data can be used as a red flag during pilot tests to indicate whether IAS may be infeasible at the site.

1.1 Current Conceptual Model of IAS Startup in a Homogeneous, Isotropic Aquifer

During IAS startup and shutdown, there are a number of parameters that are changing and those parameters can provide insight into the air distribution process. In the following discussion, it is assumed that pressure has been set at a pre-determined value to produce the desired final flow rate.

A simple conceptual model for IAS startup in homogeneous media is shown in Figure 2. When pressure is initially increased in a sparge well, water flows from the well into the formation and groundwater pressure begins to increase due to the flow of water into the formation. Once the water has been removed, air will begin to flow into the formation, the air flow rate will increase, and the groundwater pressure will rise rapidly. The extent and rate of the groundwater pressure rise will be determined by the permeability of the medium and other factors including air injection rate, injection depth, and aquifer stratification.

After a short period of more-or-less outward flow, buoyancy forces cause the air to migrate upward (as well as possibly continuing to move outward). The volume of air below the water table will continue to increase until the air reaches the water table and is "vented" to the vadose zone. At this point, the groundwater pressure passes through a maximum value and begins to drop back towards the pre-sparge hydrostatic level. In most cases, there is probably a "deflating" of the air zone below the water table because the rate of air movement out of the groundwater is faster than the injection rate. After some period of time (e.g., probably minutes in a homogeneous isotropic aquifer), a balance is reached between the volume of air being injected and the flow to the vadose zone. At a macroscopic scale, this would correspond to steady-state air flow.

1.2 Conceptual Model of IAS Startup in a Stratified Aquifer

In stratified media, the upward movement of air to the water table may be impeded or stopped by the presence of a less permeable layer (Figure 3). In these cases, there can be an accumulation of air below strata for periods of hours or even days. During this accumulation period, groundwater pressure will remain above the hydrostatic value because water continues to be displaced. The extent to which pressure rise occurs depends upon the locations of the measurement points relative to this injection well and the strata. At some point, the volume of air flowing through or going around those confining strata will become equal to the injection rate and the macroscopic air distribution will reach steady state. At that point, the groundwater pressure will have returned to near its hydrostatic value.

1.3 Conceptual Model of IAS Behavior During Shutdown

Whenever air injection is stopped, water will spontaneously begin to displace the air out of the groundwater zone (Figure 4). As this occurs, the groundwater pressure begins to decrease and remains below hydrostatic pressure while the air volume is decreasing. As with system startup, the magnitude of the hydrostatic pressure change in the formation is related to permeability.

The time required to complete the displacement process depends upon the volume of air below the water table and the pathways by which the air leaves the groundwater zone. For a homogeneous, isotropic aquifer, this process is usually completed in a few tens of minutes. For a stratified aquifer, the process can go on for hours or even days. At the conclusion of the process, there will be some residual air remaining in the formation as the result of entrapment by various mechanisms.

2.0 PRESSURE MEASUREMENTS AS A DIAGNOSTIC TOOL FOR IAS ASSESSMENT

Because IAS is a complicated, two-phase process and because there are a very wide range of subsurface conditions found at contaminated sites, it is difficult to develop an accurate picture of air distribution in the subsurface with any one technique. The best approach to understanding air distribution is to use a suite of diagnostic tools. The pressure diagnostic approach described here

compliments other field data (e.g., helium tracer tests, dissolved oxygen measurements, or geophysical measurements) and can be used both as "red flag" indicators of IAS infeasibility during pilot tests and to assess changes in system operation.

The most useful aspect of pressure measurements is the length of time over which the groundwater pressure remains above the pre-sparge hydrostatic value after IAS startup. This is a direct measure of the time over which the volume of air in the groundwater zone is increasing. If groundwater pressure remains above the pre-sparge hydrostatic value for many hours, this can be a red flag for IAS infeasibility because it indicates that a significant volume of air may be accumulating beneath low-permeability strata. As a result, air may be being deflected away from the desired treatment zone and/or lateral migration may carry contaminants to off-site receptors.

The duration of elevated pressure can also help to establish the timeframe for pulsing of air in the IAS well. As part of the Design Paradigm described by Johnson et al. (2000), pulsed air flow is recommended for IAS operation. Pulsed air flow has been demonstrated to improve contaminant mass removal from groundwater via volatilization, although it appears to have little impact on removal via biodegradation. The pattern of pressure response immediately after IAS startup provides a good indication of the length of time required for a pulse of air to propagate through the treatment area, thereby providing the practitioner a starting point for determining a pulse cycle.

The magnitude of pressure pulse can also be used to assess subsurface conditions. In general, small increases in pressure during startup indicate that the permeability of the aquifer is high, while high-pressure values generally suggest low permeability. The magnitude and duration of pressure pulses can be used together to assess air distribution. For example, if both the magnitude and duration of pressure increases are small, this indicates a very limited radius of influence of the air around the well. Conversely, pressures approaching the overburden pressure and that are sustained for periods of hours are a clear indication that the air is stratigraphically trapped. In this case, the potential exists for extensive lateral migration of the air or even pneumatic fracturing. Most sites fall somewhere between these two examples, and the practitioner must evaluate the pressure data together with data from other air distribution indictors to determine whether IAS is feasible.

One complicating factor regarding the interpretation of pressure changes is that conditions of injection pressure and flow during startup can have a significant impact on the magnitude of the groundwater pressure change. As a consequence, it is difficult to be quantitative with regard to interpreting subsurface conditions. Nevertheless, when pressure measurements are used in conjunction with other indicators, the pressure data can provide a great deal of insight into IAS air flow.

3.0 RESULTS AND DISCUSSION

IAS startup and shutdown pressure data for four sites will be examined here. The sites span a range of operating conditions (e.g., one to four IAS wells and injection rates from 5 to 20 standard cubic feet per minute [scfm]). Most sites are located in relatively permeable media that ranges from homogeneous sands and gravels to a site with extensive clay strata. The sites (in approximate order of increasing stratification) include: 1) Eielson Air Force Base (AFB), AK; 2) Port Hueneme, CA; 3) CFB Borden, Ontario, Canada; and 4) Hill AFB, UT.

3.1 Example 1: Port Hueneme, CA

The pressure data reported here for Port Hueneme were collected at Site 2, which is similar to and located approximately 100 m from the site described in Bruce et al. (2000). The unconfined aquifer at the site consists of mildly stratified sands with hydraulic conductivities from approximately 0.002 to 0.02 cm/s (Figure 5). The sparge well for these tests was screened from 4.8 to 5.1 m below ground surface (bgs). The water table at the site ranges from about 2.4 to 3 m bgs. Groundwater pressure data were collected from four 2-inch water-table monitoring wells and located at distances of 15 and 30 ft (4.6 to 9.1 m) from the sparge well. The air injection rate was approximately 10 scfm (0.27 m^3/min).

Pressure measurements following system startup and shutdown for two of the wells are shown in Figure 7. As can be seen, pressure fluctuations were on the order of tens of centimeters of water and the durations of the changes were on the order of 100 min, suggesting that steady flow had been established by that time. As a result, the IAS system at the site was operated in a pulsed mode with a cycle of 3 hours on and 3 hours off. The pressure response in the four groundwater monitoring wells during pulsed operation is shown in Figure 8. As shown, the pulse cycle of 3 hours on, 3 hours off, allows for pressure measurements to return to near hydrostatic measurements before initiation of the next pulse cycle.

3.2 Example 2: Eielson AFB, AK

The lithology of the Eielson AFB site consists of a layer of sandy loam overlying a 200 to 300 ft thick sequence of sand and gravel. In the vicinity of the IAS well, the thickness of the sandy loam is approximately 8 ft, which is also the depth to groundwater. IAS wells were installed at two depths at the site. The top of the well screen for the shallow well was approximately 4 ft below the water table, and for the deep well it was approximately 10 ft below the water table. Monitoring wells were installed at distances of 10, 20, and 30 ft from the well. Each was screened from the water table to a depth of 10 ft. A schematic diagram of the Eielson AFB test plot is shown in Figure 9. Air was injected at 5 scfm in the shallow well and 10 scfm in the deeper well.

The groundwater pressure response in the three monitoring wells to the injection of air into the shallow IAS well at a rate of 5 scfm is shown in Figure 10a. The pressure changes are very small (e.g., <1 cm water), indicating a very-high permeability at that depth. Injection at 10 scfm into the deeper well (Figure 10b) shows an order of magnitude larger pressure increase than at the shallow depth, however, the absolute value is still relatively small (e.g., <10 cm of water), indicating that the aquifer is still relatively permeable. Groundwater pressure curves for IAS shutdown at the two flow rates (Figure 10c and d) are similar in magnitude to the startup values. Also, the pressure data return to near-hydrostatic values within about an hour of startup and shutdown. This suggests that there was minimal stratification in the aquifer and that lateral migration of air will probably not be a problem at this site. However, pressure data alone cannot assess the lateral extent of the air distribution at this or most other sites. As a consequence the pressure data are best used in conjunction with other diagnostic data.

3.3 Example 3: CFB Borden, Ontario

As described in Thomson et al. (this issue) a range of IAS diagnostic tests was conducted at the CFB Borden site. The site consists of medium sand (average hydraulic conductivity of ca. 0.005 cm/s) and is composed of many small-scale beds or lenses with dimensions of a few centimeters in thickness and a few meters in areal extent (Figure 11). Unlike the other sites examined here, the vadose zone at the site had been removed so that the water table was just above ground surface. Air was injected into one of three IAS wells (Figure 12) and the pressure was monitored with pressure transducers in five piezometers.

The pressure data in Figure 13 were collected when air was injected into IAS2 at a rate of 5 scfm (0.135 m^3/min). As can be seen in the figure, the pressure quickly increases by up to 40 cm of water. The pressure remained significantly elevated for 6 hours until airflow was stopped. This indicates that during that period the volume of air was continuing to increase in the subsurface. Because the water table was above ground surface, the arrival of air at the water table could be observed as bubbles in the standing water. No significant air flow at the surface occurred for the first 30 min after sparging was initiated.

It is instructive to examine in detail the pressure changes during the first 30 min of sparging. Figure 14 shows that the pressure at all of the monitoring points began to rise in the first minute or two. For the point closest to the sparge well (p3-1), the pressure reached a maximum and began to fall after about 7 min (even though no air had reached the water table, which is in contrast to the conceptual model discussed above). The monitoring points that were 10 ft (3 m) away (p4-1 and p4-2) also reached a maximum in that same interval, but decreased at a slower rate. This was particularly true for the deeper point (p4-2), which had decreased only about 20% from the maximum value after 30 min. The two points at 20 ft (p5-1 and p5-2) did not go through a maximum during the first 30 min, but continued to rise over the whole interval. These data point out the complexities associated with interpreting pressure data in stratified media, particularly in the absence of other corroborating information. Nevertheless, the period over which the pressure is elevated does clearly indicate that a substantial volume of air was accumulating below the water table.

Following cessation of air injection, the groundwater pressure dropped and remained below the hydrostatic value for approximately 4 hours. During that period, air continued to flow out of the saturated zone (as evidenced by bubble flow at the surface). Prior to cessation, the air flow at the surface appeared quite steady and when injection stopped, the flow to the water table continued with little if any change. The air flow rate at the water table was estimated as a function of time following cessation and is shown in Figure 15. Based on that data, the volume of trapped air was estimated to be approximately 28 m^3, which corresponds to about 200 minutes of injection at 5 scfm.

3.4 Example 4: Hill AFB, UT

The water-bearing zone at Operable Unit (OU)-6, Hill AFB is composed primarily of sands and silty sands. It is overlain by silt with beds of sand and clay. The interface between these two is near the current water table at approximately 105 ft below ground surface (Figure 16). A line of four sparge wells with co-located soil vapor extraction (SVE) wells was placed across a portion of a

dissolved trichloroethene (TCE) plume which was exiting the base boundary (Radian, 1995). In addition, nests of monitoring wells were distributed around the treatment zone. The locations of the wells are shown in Figure 17. The total injection rate was approximately 50 scfm for the four wells.

Groundwater pressure increases in excess of 300 cm were observed at the wells closest to the injection well. Pressure increases of nearly 200 cm were observed even at a distance of 130 feet (Figure 18). The pressures remained elevated for nearly two days, until the sparging system was turned off. This is indicative of an extensive layer that is effective at preventing upward migration of the air and is consistent with the helium tracer data for the site (Johnson et al., 2000b). Vertical permeability was measured using intact soil cores from the site in a constant-head permeameter. The data are shown in Figure 19 and indicate that there is a very high conductivity layer at about 125 feet bgs and that the conductivity decreases by several orders of magnitude in the upper portions of the saturated zone. If the lower-permeability layer is extensive, then this permeability contrast would be sufficient to cause the stratigraphic entrapment of the air inferred from the pressure data.

At this site, the bulk of the contaminated groundwater lay below the confining layer so the sparge air was able to be reasonably effective at removing contaminants. However, the system was not capable of lowering concentrations to the drinking water limit (5 μg/L for TCE in this case). Furthermore, there is some concern that the large volume of air trapped below the water table may have had a significant impact on the water permeability of the aquifer (as was seen, for example, at the CFB Borden site) and could have caused part of the plume to have been diverted around the treatment zone.

4.0 CONCLUSIONS

For many sites, groundwater pressure responses during startup and shutdown provide important insight into air movement below the water table. If lag times of hours to days are required for groundwater pressures to return to within a few cm of water of pre-sparge hydrostatic values, this indicates that there is significant stratigraphic trapping of air. Stratigraphic trapping can be either good or bad, depending where the confining layer is located relative to the zone to be treated and to risk pathways. For many sites, some degree of stratification is necessary to increase the width of the treatment zone to a scale that makes sparging practical. However, too much stratification can cause excessive lateral migration or it may prevent the sparge air from reaching the treatment zone.

In general terns, the magnitude of pressure responses during startup and shutdown can be viewed as proportional to air flow rate and inversely proportional to aquifer permeability. However, there is currently no overall modeling framework that allows the magnitude of the pressure responses to be directly related to unique characteristics of the aquifer and/or air distribution.

Because pressure measurements are easy and rapid to collect, they are a useful component of pilot tests, where they can act as a "red flag" for IAS infeasibility. They are also useful for evaluating system operating parameters (e.g., pulse cycle times, air flow rates) because the tests can be repeated quickly following changes in system parameters. In either case, the pressure data are best used in conjunction with other diagnostic tools, which collectively can present an overall picture of IAS performance.

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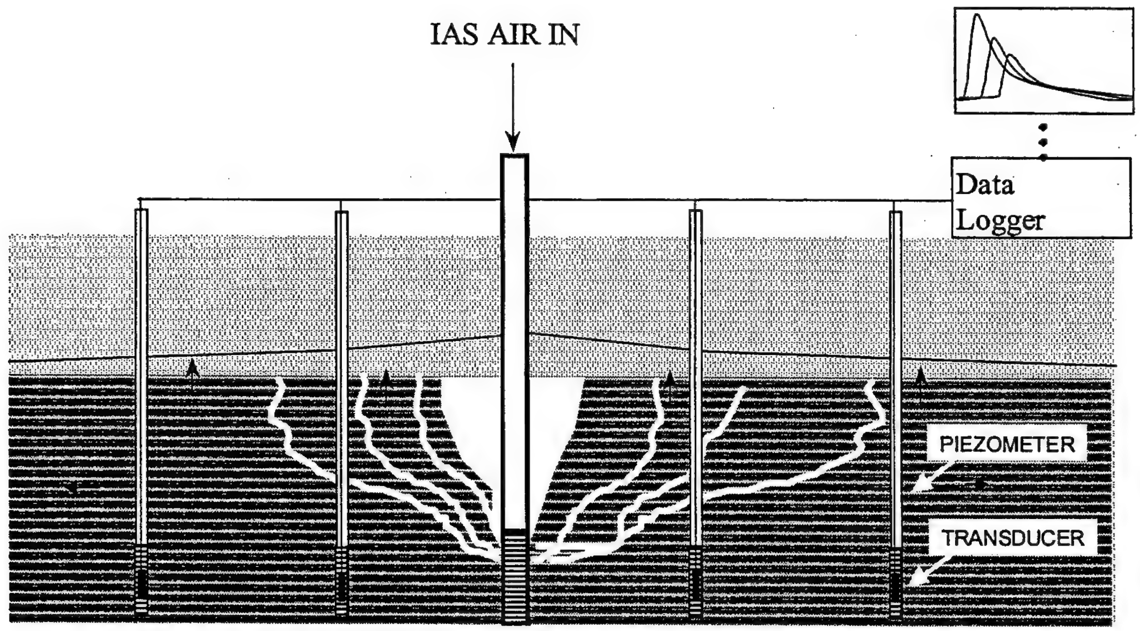
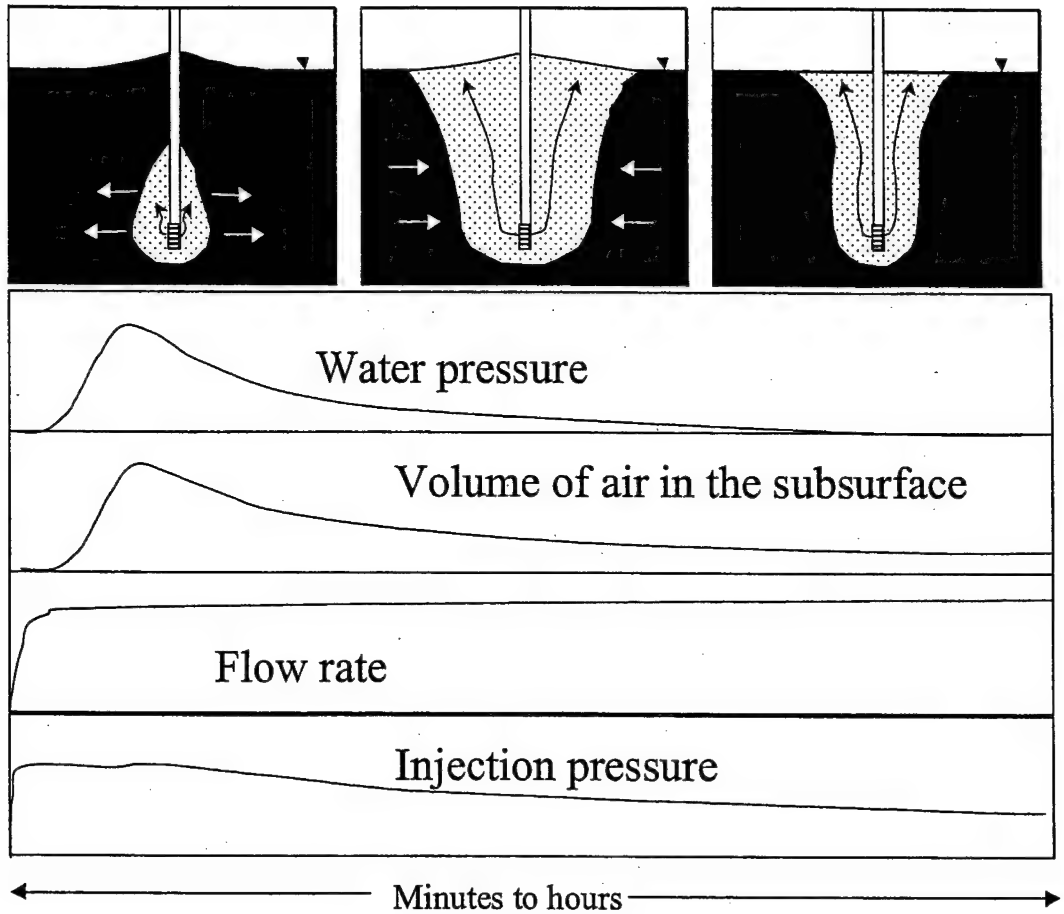
Figure 1. Schematic Drawing of Water Pressure Measurement During IAS Startup





Water pressure
Volume of air in the subsurface
Flow rate
Injection pressure
Minutes to hours

Figure 2.

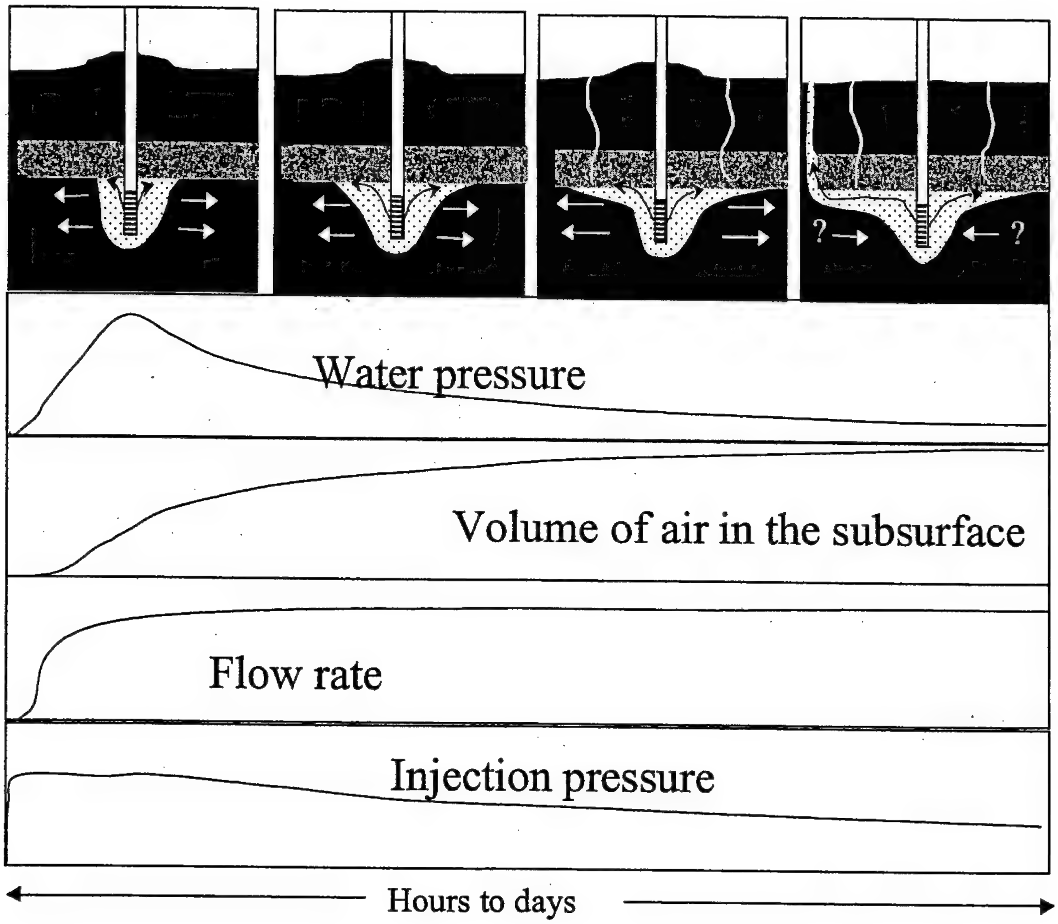

?
?
Water pressure
Volume of air in the subsurface
Flow rate
Injection pressure
Hours to days

Figure 3.

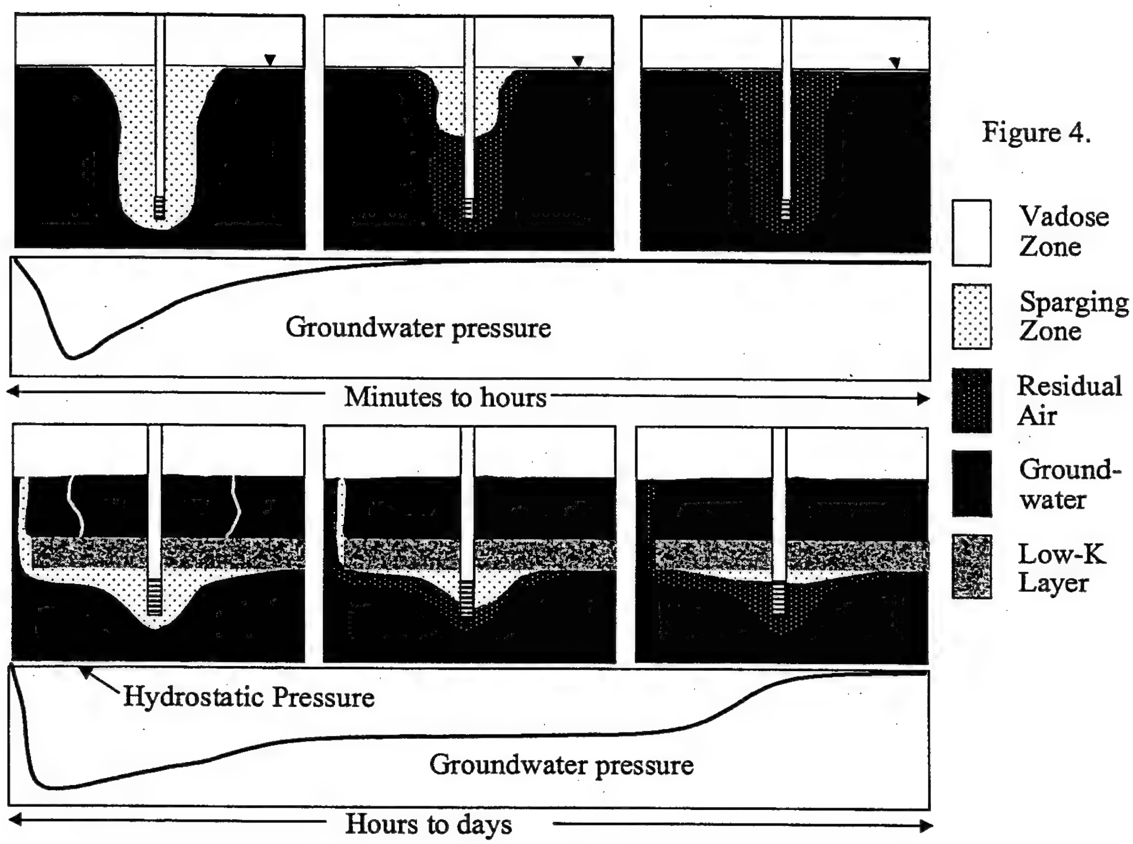


Figure 4.
Vadose Zone
Sparging Zone
Residual Air
Ground-water
Low-K Layer
Groundwater pressure
Minutes to hours
Hydrostatic Pressure
Groundwater pressure
Hours to days

Figure 4.

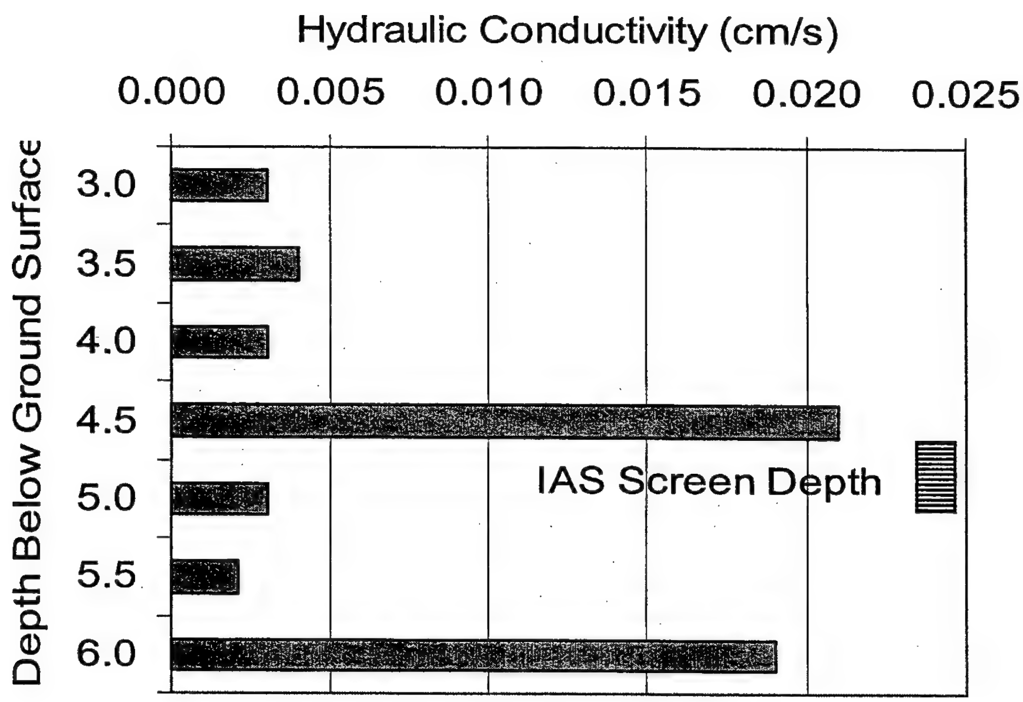

Hydraulic Conductivity (cm/s)
0.000
0.005
0.010
0.015
0.020
0.025
Depth Below Ground Surface
3.0
3.5
4.0
4.5
5.0
5.5
6.0
IAS Screen Depth

Figure 5

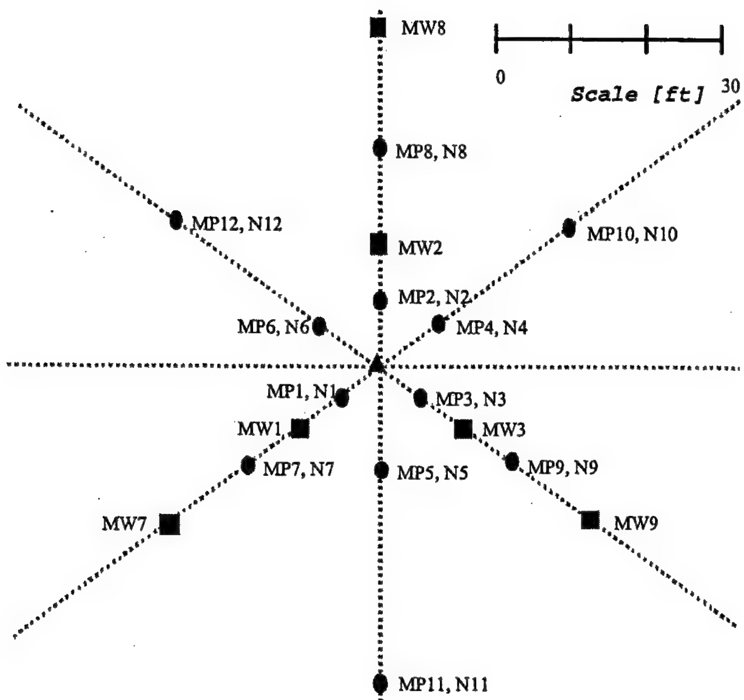
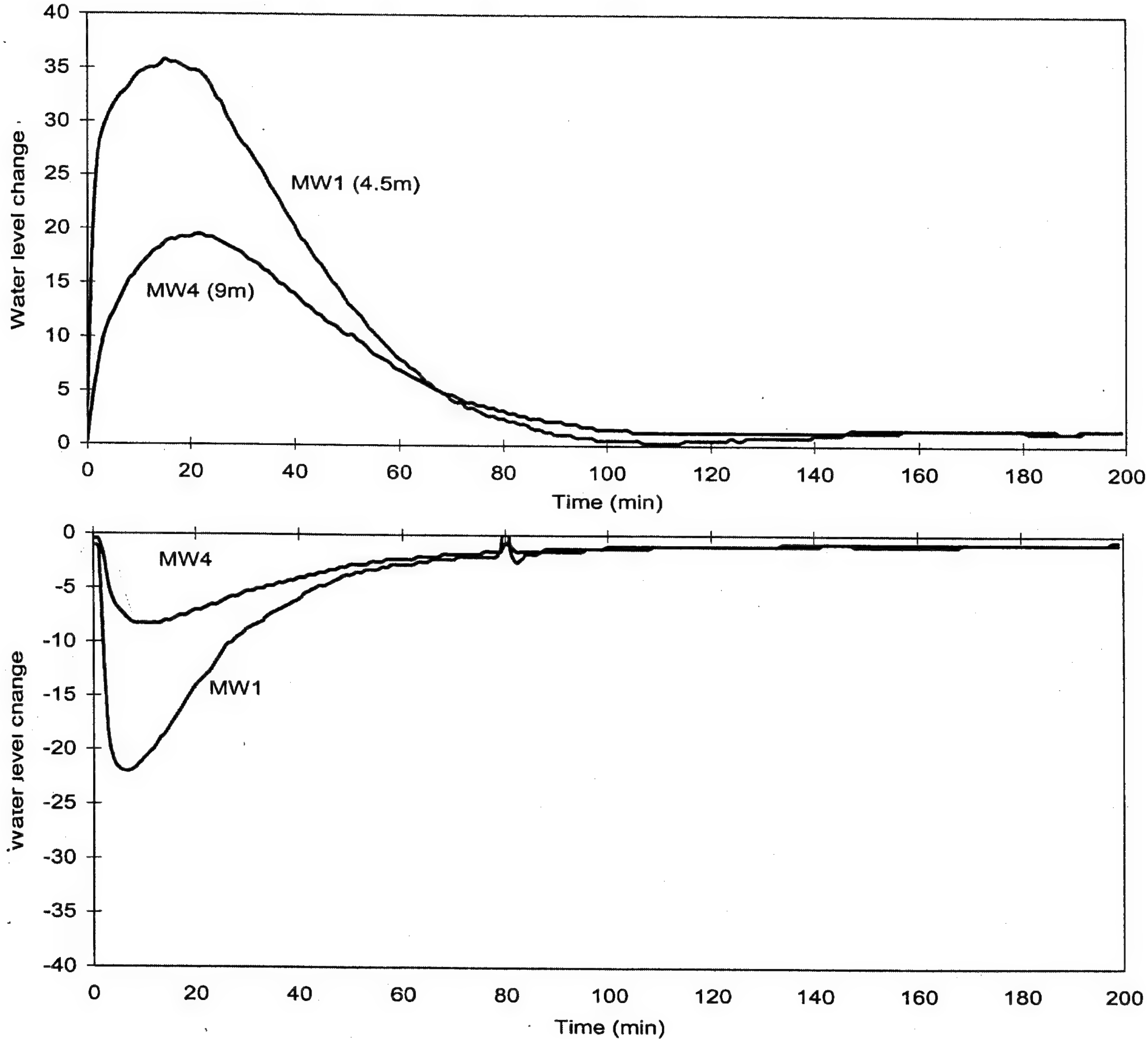
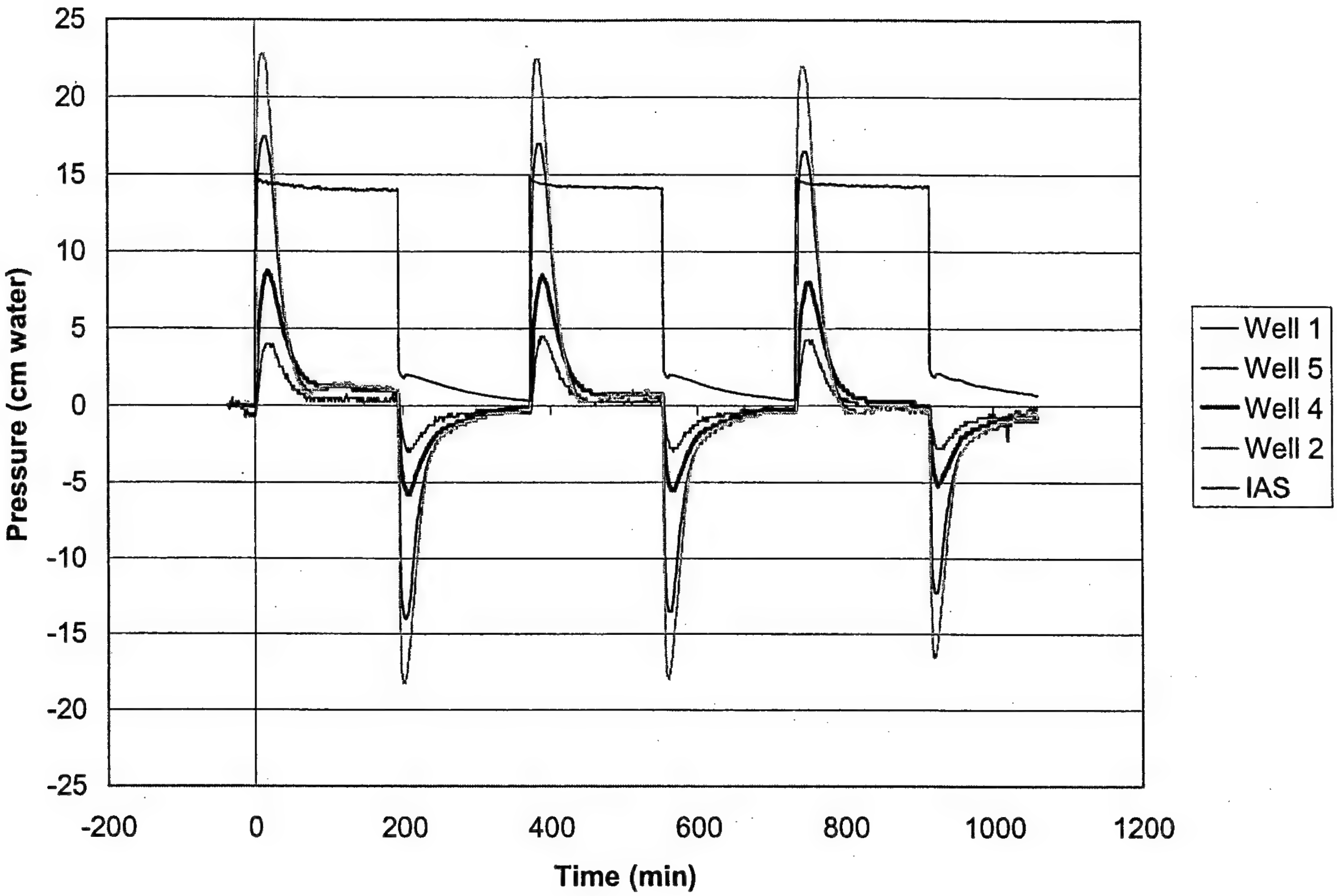

MW8
0
Scale [ft]
30
MP8, N8
MP12, N12
MW2
MP10, N10
MP2, N2
MP6, N6
MP4, N4
MP1, N1
MP3, N3
MW1
MW3
MP7, N7
MP5, N5
MP9, N9
MW7
MW9
MP11, N11

Figure 6



MW1 (4.5m)
MW4 (9m)
Water level change
Time (min)
MW4
MW1
Water level change
Time (min)

Figure 7



25
20
15
10
5
0
-5
-10
-15
-20
-25
Pressure (cm water)
-200
0
200
400
600
800
1000
1200
Time (min)
Well 1
Well 5
Well 4
Well 2
IAS

Figure 8.

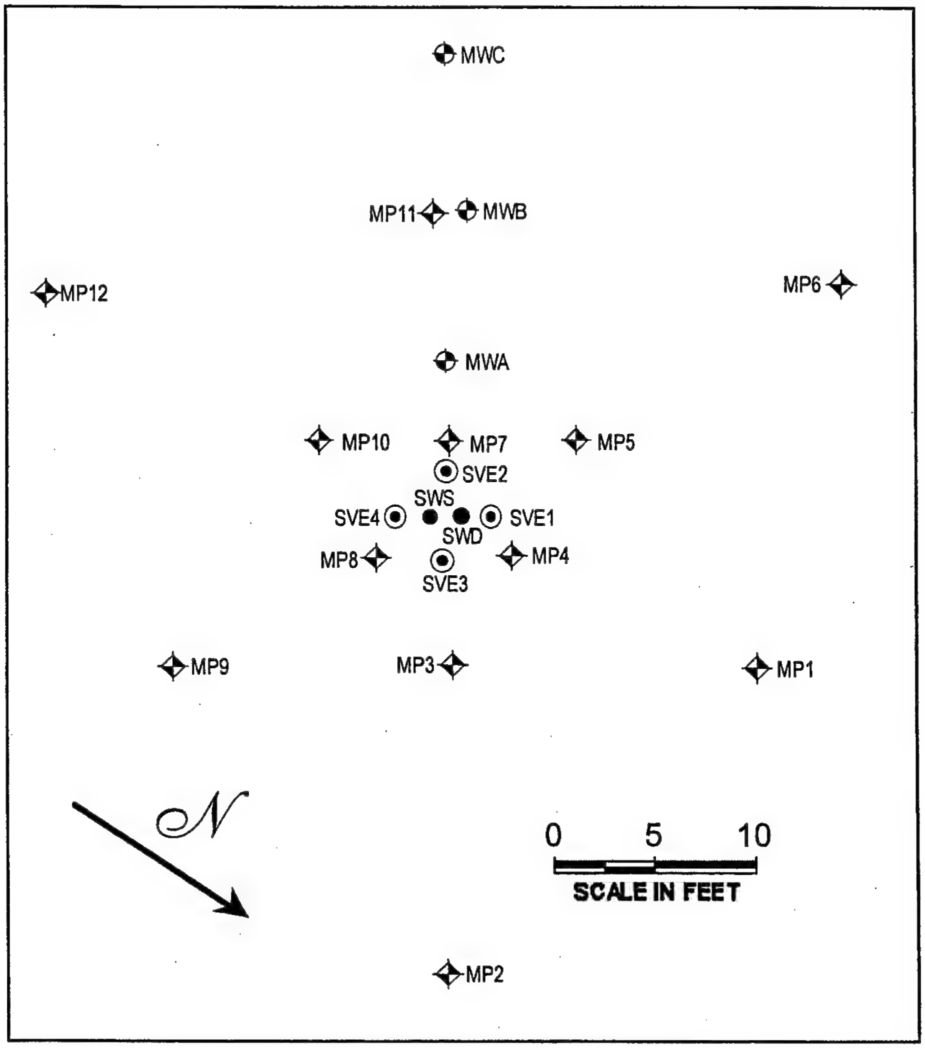

MWC
MP11
MWB
MP12
MP6
MWA
MP10
MP7
MP5
SVE2
SWS
SVE4
SVE1
SWD
MP8
MP4
SVE3
MP9
MP3
MP1
N
0
5
10
SCALE IN FEET
MP2

Figure 9.

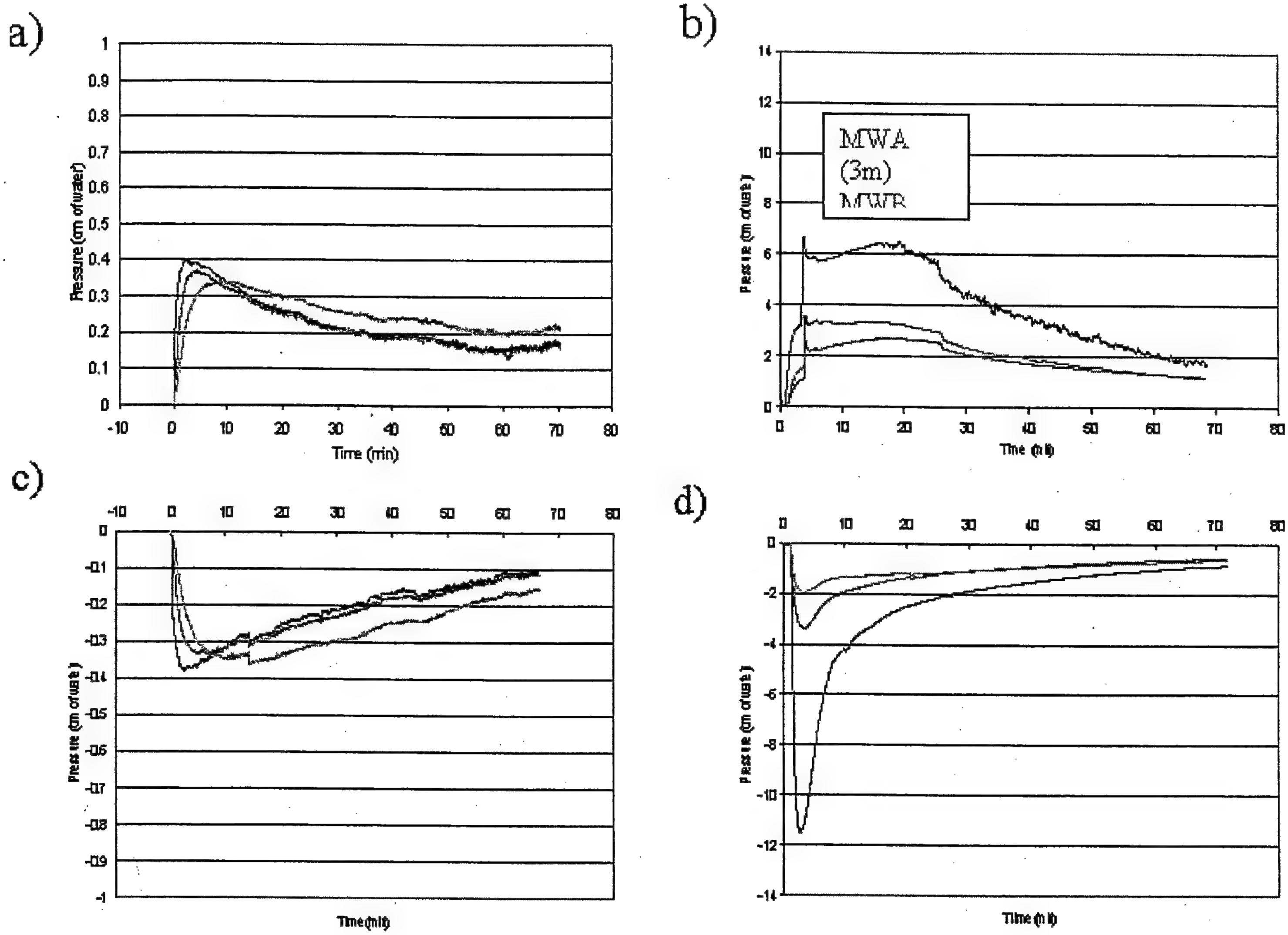


Figure 10.

Picture of Borden permeability field

Figure 11.

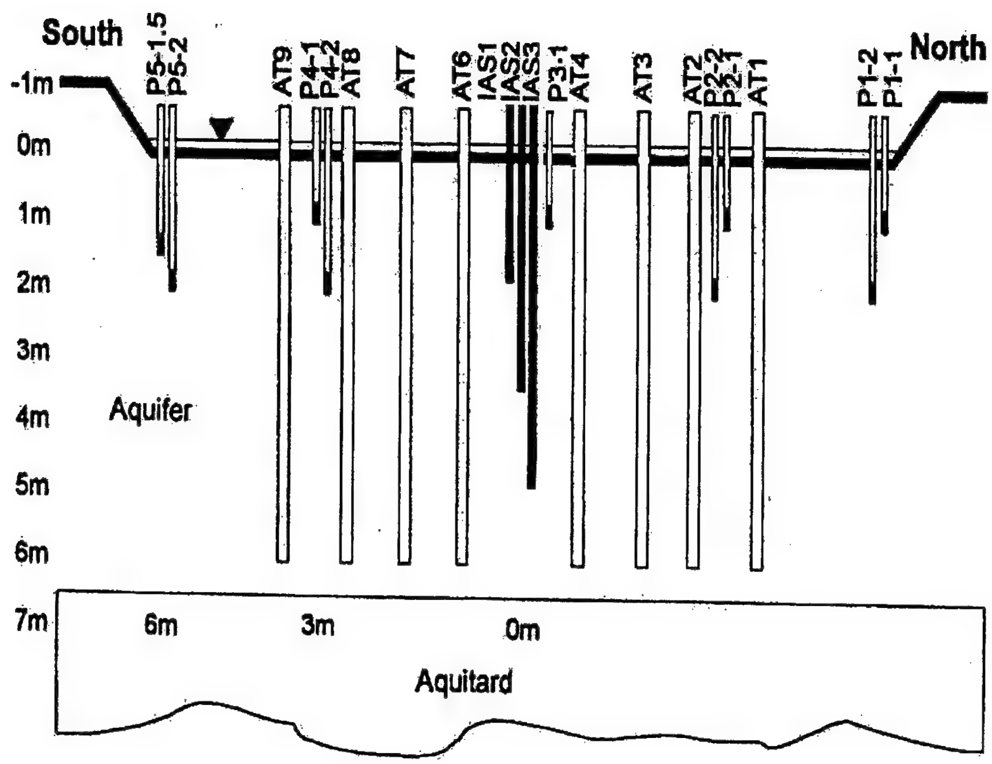
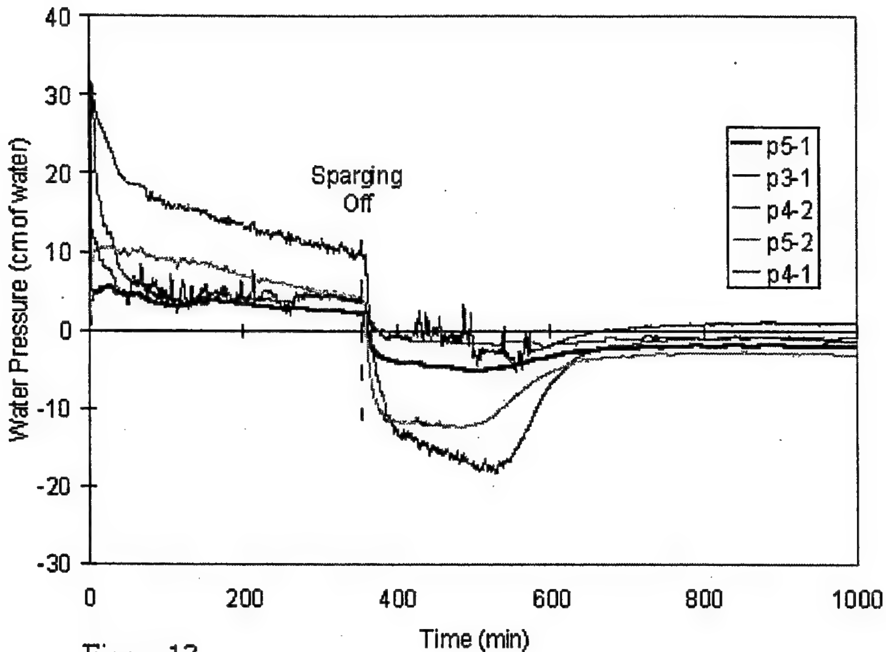
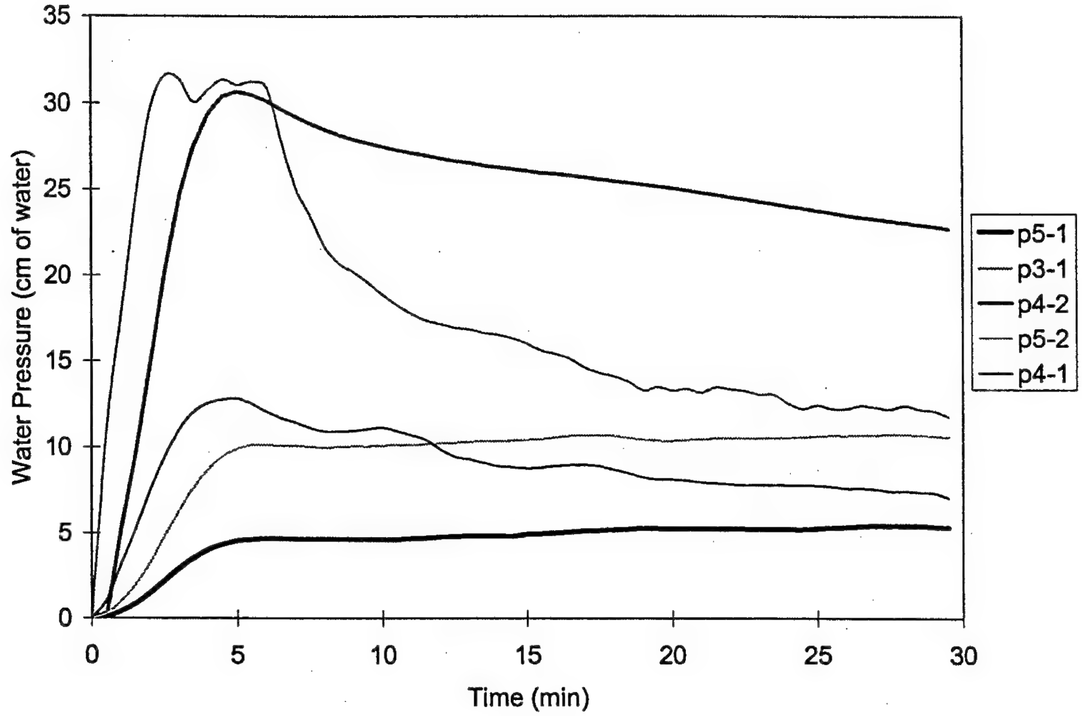

South
North
P5-1.5
P5-2
AT9
P4-1
P4-2
AT8
AT7
AT6
IAS1
IAS2
IAS3
P3-1
AT4
AT3
AT2
P2-2
P2-1
AT1
P1-2
P1-1
-1m
0m
1m
2m
3m
4m
5m
6m
7m
Aquifer
6m
3m
0m
Aquitard

Figure 12.



40
30
20
10
0
-10
-20
-30
Water Pressure (cm of water)
0
200
400
600
800
1000
Time (min)
Sparging
Off
p5-1
p3-1
p4-2
p5-2
p4-1

Figure 13.



Water Pressure (cm of water)
35
30
25
20
15
10
5
0
0
5
10
15
20
25
30
Time (min)
p5-1
p3-1
p4-2
p5-2
p4-1

Figure 14.

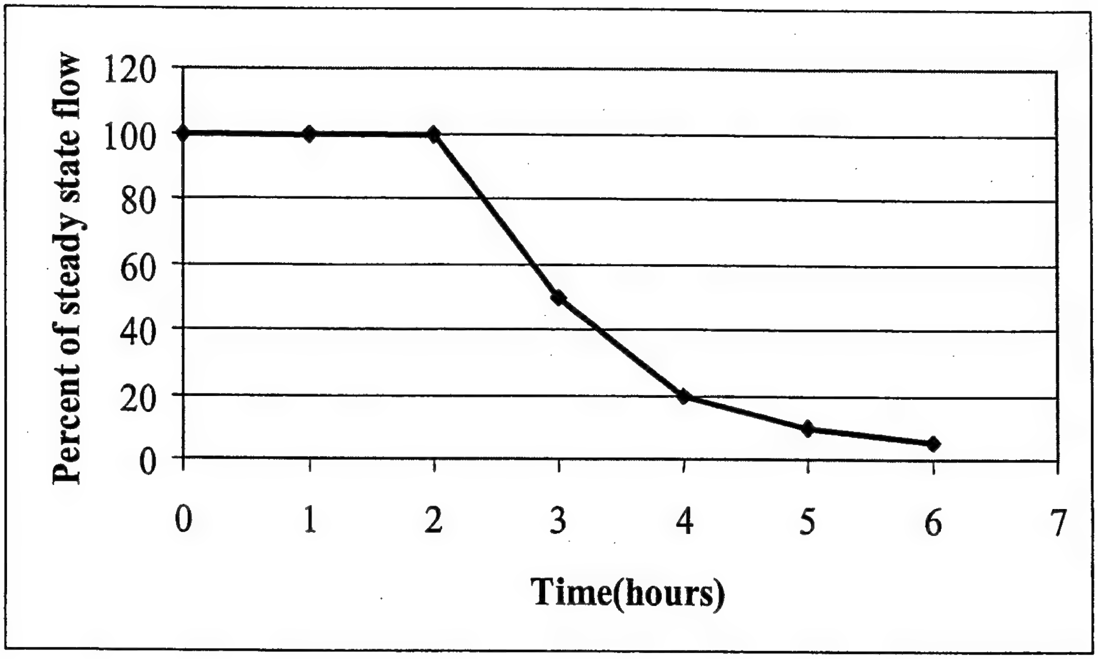
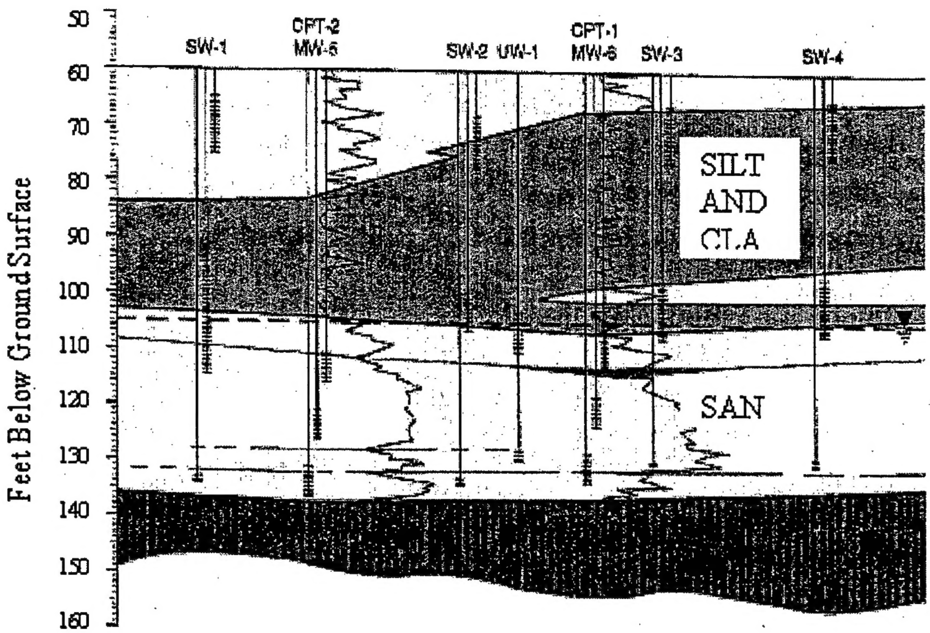

Percent of steady state flow
120
100
80
60
40
20
0
0
1
2
3
4
5
6
7
Time(hours)

Figure 15.



Feet Below Ground Surface
50
60
70
80
90
100
110
120
130
140
150
160
SW-1
CPT-2
MW-5
SW-2
UW-1
CPT-1
MW-6
SW-3
SW-4
SILT
AND
CLA
SAN

Figure 16.

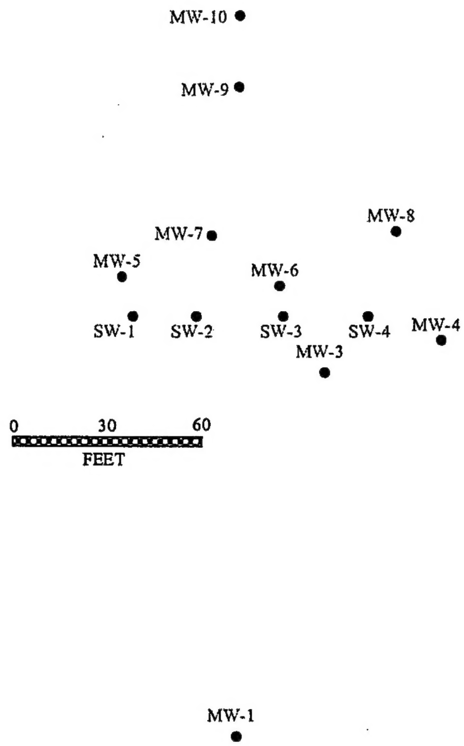
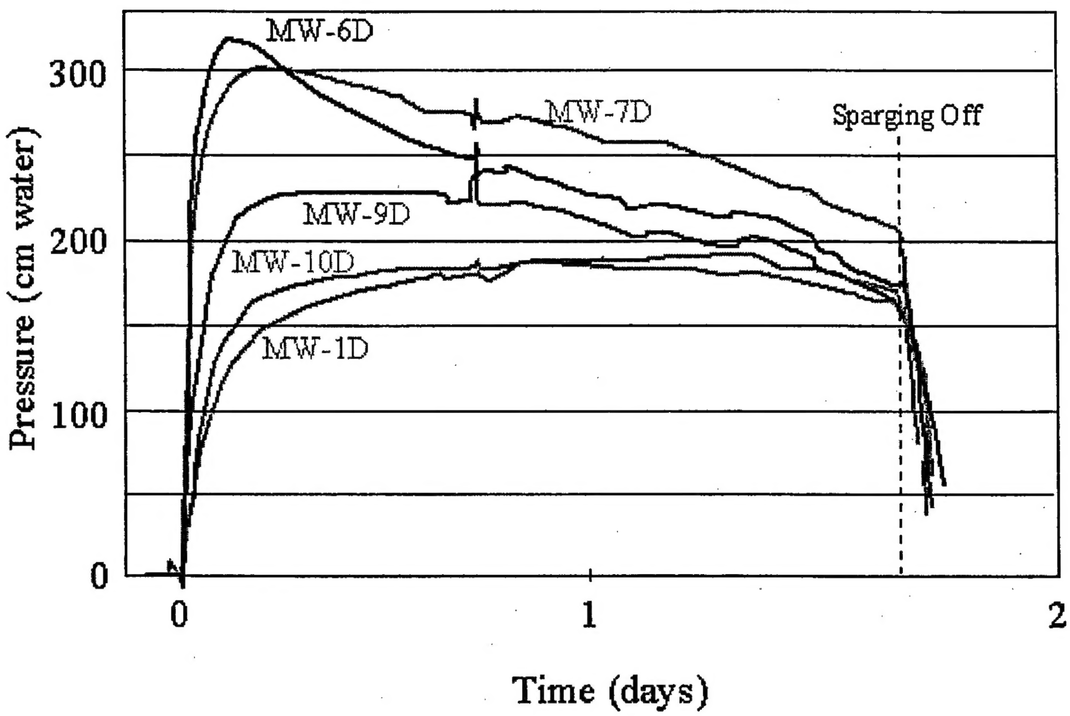
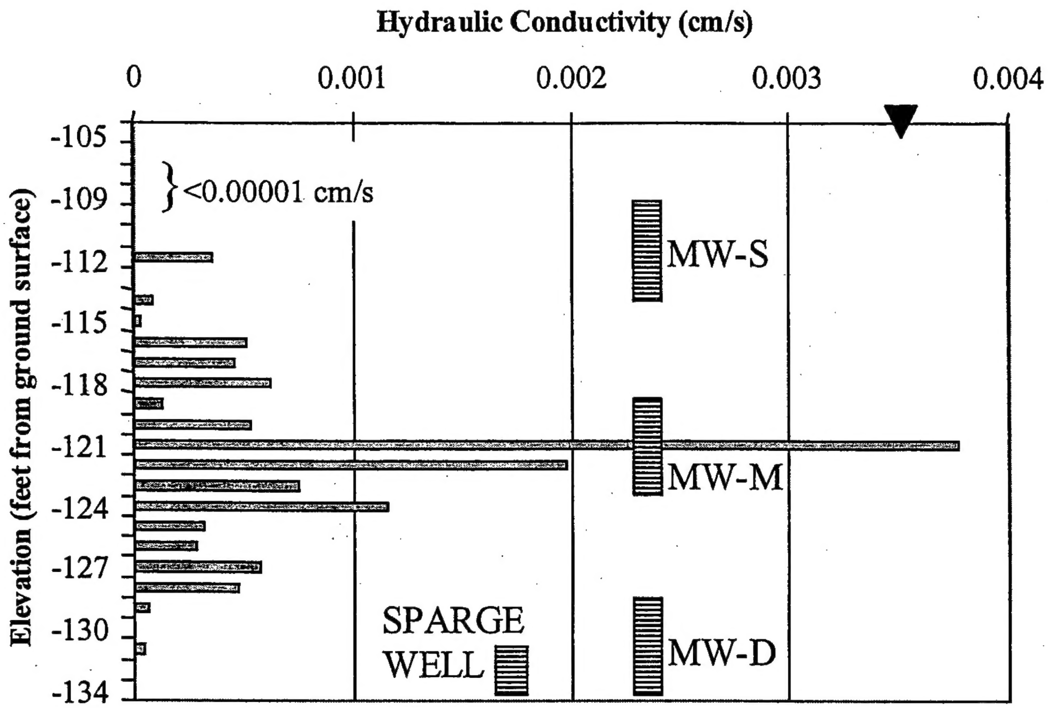


Figure 17.



MW-6D
MW-7D
Sparging Off
MW-9D
MW-10D
MW-1D
300
200
100
0
Pressure (cm water)
0
1
2
Time (days)

Figure 18.



Hydraulic Conductivity (cm/s)
0
0.001
0.002
0.003
0.004
Elevation (feet from ground surface)
-105
-109
-112
-115
-118
-121
-124
-127
-130
-134
<0.00001 cm/s
MW-S
MW-M
MW-D
SPARGE
WELL

Figure 19.